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OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

Radiological Assessment of Residences in the Oak Ridge Area

Vol. 1—Background Information for ORNL Environmental Impact Statement

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RADIOLOGICAL ASSESSMENT OF RESIDENCES IN THE OAK RIDGE AREA

VOL. 1 — BACKGROUND INFORMATION FOR ORNL ENVIRONMENTAL IMPACT STATEMENT

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ABSTRACT

Measurements of exposure rates using thermoluminescent dosimeters placed within residences in the Oak Ridge/Knoxville area are presented. The objective of this investigation was to determine the radiation component acquired by Oak Ridge National Laboratory employee personnel dosimeter-security badges during residential badge storage and to develop a model to predict the radiation exposure rate in Oak Ridge/Knoxville-area homes. The exposure rates varied according to building material used and geographic location. Exposure rates were higher in the fall and lower in the spring; stone residences had a higher average dose equivalent rate than residences made of wood. An average yearly exposure rate was determined to be 78 millirems per year for the Oak Ridge-area homes. This value can be compared to the natural background radiation dose equivalent rate in the United States of 80 to 200 millirems per year.

1. INTRODUCTION

The largest source of radiation exposure to man is the natural radiation in the environment. Man is exposed to natural radiation in varying degrees; this exposure depends on such factors as geographic location, building construction materials, etc. Radiation contributions from cosmic rays, radionuclides of terrestrial origin, and those radionuclides present within the body account for most of the natural radiation exposure. The average annual dose equivalent from natural background radiation to people living in the United States is considered to be between 80 and 200 millirems per year.[1] This dose equivalent may be compared to a genetically significant dose equivalent average of 55 millirems per year received from x rays utilized for medical diagnostic purposes.[2] The combination of other man-made sources of radiation (e.g., nuclear weapons fallout, nuclear reactors) contribute less than 5 millirems per year.[2]

Since the beginning of the Neolithic Age (approximately 10,000 B.C.), the amount of natural radiation has remained relatively constant. It was noted by Black[3] that the most recent reversal of the earth's magnetic field (estimated to have occurred about 700,000 years ago) may have caused a 10% increase in the natural radiation at the earth's equatorial regions. This increase was attributed to an increase in cosmic rays and had an estimated duration of approximately 1000 years. With the exception of short-term variations in the cosmic-ray flux density caused primarily by solar flares, no significant changes in the natural radiation environment have been noted in the literature. The various components of the natural radiation background are described in the remainder of this section.

1.1 Cosmic Radiation

Cosmic rays are the natural radiation contribution from above the surface of the earth. At sea level, they consist of an ionizing component (μ-mesons and electrons), a neutron component, and a minor contribution from electromagnetic radiation. The μ-meson component accounts for approximately 70% of the dose from cosmic radiation and is the most significant component of population exposure.

Galactic radiation from outside our solar system and solar radiation from phenomena on the sun are the primary sources of cosmic rays. These two types of cosmic radiation contribute high-energy particles thought to exceed 1×10^{10} GeV in energy, with an average energy flux density of 2×10^3 MeV cm^{-2} sec^{-1} arriving at the earth's upper atmosphere.[4] Galactic radiation is estimated to be 75 to 89% protons, 10 to 18% helium nuclei and 1 to 7% nuclei with an atomic number greater than 3; solar radiation consists primarily of protons and helium nuclei.[1,5,6]

The average dose equivalent caused by cosmic radiation in the United States is 40 millirems per year; it is approximately 45 millirems per year in Tennessee. Cosmic radiation fluctuations on the earth can be attributed to variations in altitude and latitude. The latitude effect is a phenomenon that causes a 12% increase in cosmic ray intensity at the poles (relative to the equator).[7] The whole-body dose equivalent rates at sea level from Alaska to Florida range from 45 to 50 millirems per year.[8] Estimates of the neutron component are more difficult because of uncertainties in the spectral quality of the neutron flux density. However, at sea level in the middle latitudes, the neutron dose equivalent rate is considered to be about 7 millirems per person-year.[9]

1.2 Terrestrial Radiation

A significant portion of the background radiation exposure is caused by the naturally occurring radionuclides in the earth. The major radionuclides of significance to man's terrestrial gamma radiation dose are ^{40}K and the nuclides in the decay chains of ^{238}U and ^{232}Th. Other additional nuclides are present in the rocks and soil but are considered insignificant because of their relatively low concentrations.[10]

At the surface of the earth, the neutron component of cosmic rays via neutron capture results in the production of additional radionuclides; ^{14}C and ^{3}H are some examples of these interactions. The dose equivalent from this process is considered insignificant.

Terrestrial radiation varies as a function of geographic location. The highest terrestrial gamma radiation values have been observed in the vicinity of acidic rocks (e.g., granite). Dose rates in monazite areas (e.g., sands on certain beaches of Rio de Janeiro, Brazil) have been reported to be as high as 1300 millirems per year.[11] Principle constituents in these areas are primarily radionuclides from the ^{232}Th decay series. Table 1.1 gives exposure values of background radiation for specific locations throughout the United States.[1]

1.2.1 Radon daughter products in natural terrestrial radiation

Variability in the natural aboveground radiation level is primarily caused by the concentration of radon daughters in the atmosphere. A daughter product of the ^{238}U decay series, ^{222}Rn ($T_{1/2}$ = 3.8 d), and a daughter product of the ^{232}Th decay series, ^{220}Rn ($T_{1/2}$ = 54.4 sec), contribute a few millirems per year to the dose equivalent rate.[12] Both ^{222}Rn and ^{220}Rn have short-lived daughter nuclides that become attached to particulates in the air, which increases the potential for their inhalation.

Atmospheric temperature inversion, low barometric pressure, and low soil moisture increase emanation of radon from the ground, resulting in high concentrations of radon daughters in the air.[13] Beck, et al.[14] indicated that the ^{40}K exposure rate decreases 30% when the soil water increases from 0 to 30%. This increase in moisture content effectively increases the shielding capacity of the soil. It has also been shown that reduced radon gas emanation from the soil occurs when the soil moisture content increases. This increase in soil moisture decreases the ^{40}K exposure and either increases or leaves unchanged the ^{222}Rn content. Another parameter affecting the variability of radon emanation from the ground is snow cover. Snow cover essentially provides entrapment of radon gas in the soil, consequently decreasing radiation exposure.[15]

1.2.2 Natural radiation exposure from building materials

The radiation exposure to man within a building is affected by the composition of the building materials, the geometry of exposure, and the

Table 1.1 Ground surveys of background radiation in the United States

Location	Instrumentation	Value (millirems per year)	Remarks
38 U.S. towns and cities	Ion chamber	73–197	125 measurements
30 locations near San Francisco	Portable scintillator	39–108	
Approximately 210 locations in 25 states	Spectrometer and ion chamber	4–180	2–3 measurements per location, some taken in different years
New Hampshire and Vermont	Personal dosimeters (ion chambers)	119–171	400 measurements
New Hampshire	Spectrometer	45–95	Outdoors
Vermont	Portable scintillator	0.7 × out-door values	Indoors in 160 homes and apartments
30 locations near San Francisco	Portable scintillator	35–102	
1102 towns in 24 states	Portable scintillator	59–116	9026 measurements; all states were east of the Mississippi River except Iowa, Minnesota, and Colorado
Florida — near phosphate beds	Portable scintillator	59–115	1161 measurements, the majority in southwestern Polk County

Table 1.1 (continued)

Location	Instrumentation	Value (millirems per year)	Remarks
Boston	Ion chamber	83–121	6 measurements outdoors
		61–105	15 measurements in 6 frame dwellings
		81–114	3 measurements in 3 apartments
		73–118	16 measurements in 4 office buildings
Livermore, Calif., inside 110 homes	Thermoluminescent dosimeters	32–75	All frame homes except 4

Source: Adapted from D. T. Oakley, *Natural Radiation Experience in the United States*, USEPA Document ORP/SID 72-1, 1972.

duration spent at each location. Other factors influencing the exposure rate include the concentration of radionuclides present within the building materials, the ventilation rate, and the type of surface on the inner walls.

The average urbanite spends approximately 80% of his lifetime indoors,[16] where exposure to natural radiation consists primarily of radon daughters emanating from building materials. This radiation exposure has been shown to be substantially higher in buildings constructed of bricks, low-density concretes, granites, and calcined gypsum materials[17,18] (Table 1.2).

Frame dwellings have relatively low indoor radiation levels; radiation exposure within frame structures is 70 to 80% that of outdoor values.[19] In masonry buildings, indoor exposure is 80 to 106% that of outdoor radiation values.

Meteorological parameters affecting the dose equivalent rate from building materials have been studied extensively.[18] Barometric pressure, soil temperature, wind speed, and relative humidity are among the meteorological parameters that act simultaneously to control releases of ^{220}Rn, ^{222}Rn, and their short-lived daughter products from building materials. Steinhäusler[19] indicated that a seasonal effect occurred varying the ^{222}Rn, ^{214}Pb, and ^{212}Pb levels from a brick control building.[19] Strong inversion layers during the winter months caused an enrichment of radionuclides in the lower atmosphere corresponding to maximum levels in the winter, while minimum values were detected in May.

Another minor contribution to the dose received by man in buildings can be attributed to ^{222}Rn in natural gas. In rooms containing unvented gas kitchen ranges and space heaters, tracheo-bronchial dose equivalents were reported as 15 and 54 millirems per year, respectively.[20] Other reports on radon in natural gas suggest that exposure to the radon component in natural gas can be considered to be negligible to the total natural radiation dose.[21]

Table 1.2. Naturally occurring radionuclide concentration estimates of Ra, U, Th, and K in building materials (ppm)

Material	Radium	Uranium	Thorium	Potassium
Clay bricks	1.4	9.6	11.2	2.1
Granite aggregate	0.3	4.5	3.2	2.0
Granite bricks	2.4	19.0	20.5	3.5
Cement	ND[a]	3.4	5.4	0.8
Limestone concrete	ND	2.3	2.1	0.3
Sandstone concrete	ND	0.8	2.1	1.3
Dry wallboard	ND	1.0	3.0	0.3
Vermiculite (potassium mica)	2.5	0.3		4.6
Gypsum Type A (waste product of super-phosphate fertilizer)	21.3	10.7	4.3	0.2
Gypsum Type A (carbonatite ores)	3.2	ND	5.9	ND
Gypsum Type B (natural gypsum)	0.6	1.2	1.9	0.5

[a]Not determined.

Sources: Adapted from E. I. Hamilton, "The Relative Radioactivity of Building Materials," *Am. Ind. Hyg. Assoc. J.*, June 1971; and National Council on Radiation Protection and Measurements, *Radiation Exposure from Consumer Products and Miscellaneous Sources*, Report No. 56, 1977.

2. METHODS AND MATERIALS

2.1 Thermoluminescent Dosimeter (TLD) Description and Grading Procedure

Two 0.32 × 0.32 × 0.089-cm LiF thermoluminescent dosimeters (TLDs) (TLD-100, The Harshaw Chemical Co.) with a natural isotopic composition of 7.5% ^{6}Li and 92.5% ^{7}Li were placed in a Lucite TLD ring holder and then placed into polyethylene bottles containing 3 g of 6-16 mesh silica gel desiccant (Fig. 2.1). These polyethylene bottles were distributed to the homes of various ORNL employees in the East Tennesseee area for the study.

All TLDs were graded initially for their response per unit exposure to a radium source. The grading procedure began by annealing the TLDs for 30 min at 400°C and then heating them for 2 h at 100°C. They were then exposed to a 102.67 mg radium source (in radioactive equilibrium) encased in 1-mm-thick Monel (alloy composition — 60% nickel, 33% Cu, 7% iron with ρ = 8.9 g/cm^3). This cylindrical source was 0.84 cm long with a 0.07 cm diameter. This source was calibrated with an NBS source. Exposure rate was calculated in millirems per hour by:

$$\text{milliR/h} \cong \frac{MK}{d^2}$$

where

M = absolute amount of radium (mega Bq)

$K = 8600 \dfrac{(\text{milliR})(\text{cm}^2)}{(\text{h})(\text{mega Bq})}$ (correction factor for 1-mm Monel encasement)

d = distance from source (cm)

Each TLD was then irradiated in the Lucite TLD ring holder 13.7 cm from the source for 78 sec to obtain an exposure of 100 millirems. The apparatus for TLD source exposure has been previously described.[22] The Lucite TLD ring holder (1 g/cm^2 thickness) afforded good geometry for exposure with a minimum of scattering.

ORNL-PHOTO 2739-76

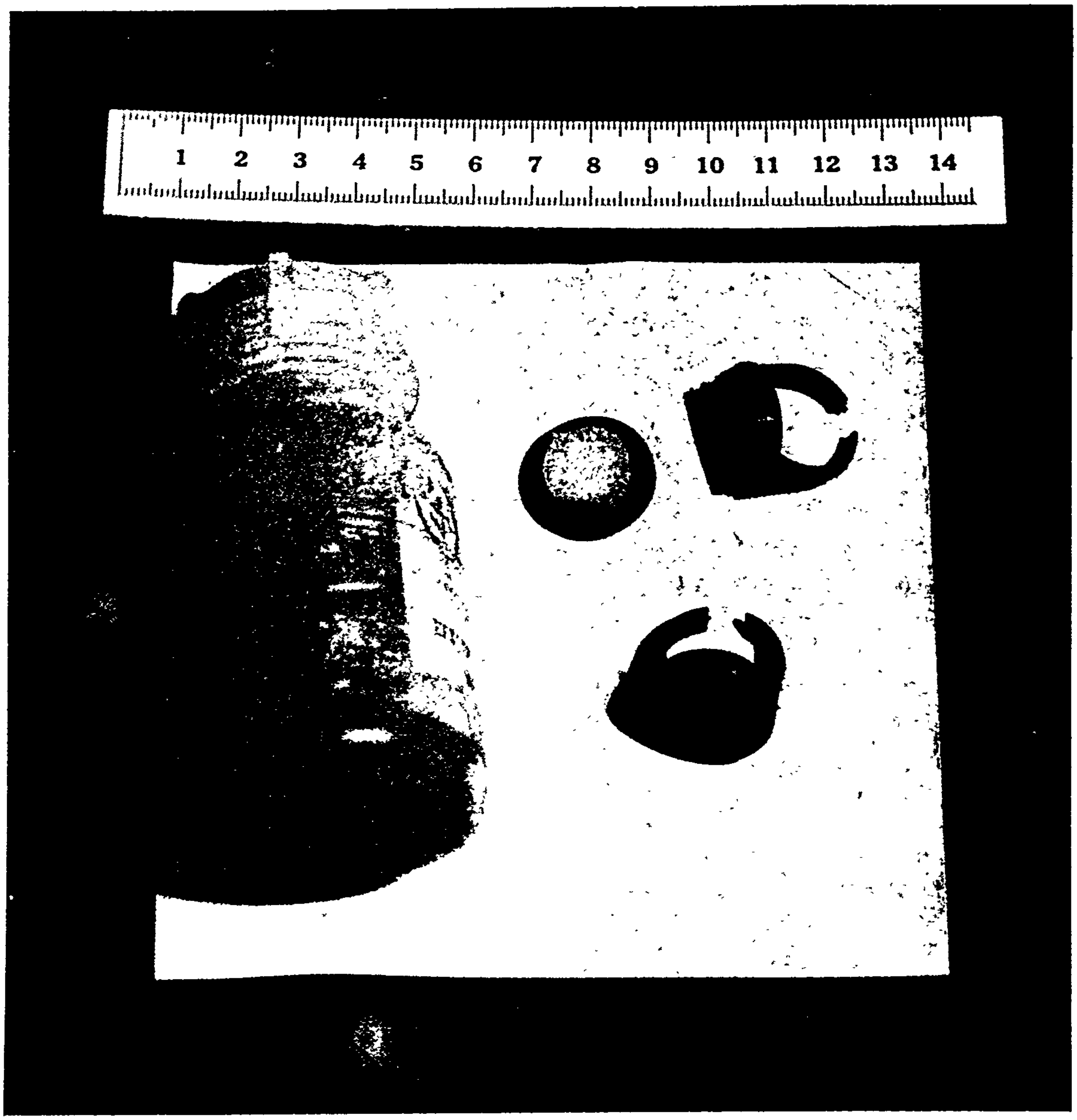

Fig. 2.1. Polyethylene bottle containing lucite TLD holder and silica gel.

After irradiation, the TLDs were oven-tempered at 80°C for 20 min and then read in a TLD reader. Glow curves for the TLD-100s have been previously reported.[23] The TLDs that showed similar response per unit exposure to the radium source were then used for this study.

2.2 TLD Handling and Readout Procedure

Each TLD chip was handled carefully to decrease the probability of damage and consequently to decrease change in TLD response. Control TLDs were placed into a cylindrical lead encasement (4-in.-thick walls) to minimize background radiation contributions. At the midpoint of each three-month period, one set of control TLDs was irradiated with 100 milliR from the described radium source and returned to the lead shielding. These control TLDs, as well as the TLDs distributed to the houses, were read the same day. The TLDs were read as soon as they were returned from the houses to decrease the amount of storage time and consequent fading.

All TLDs returned were pretreated before reading by oven-tempering at 80°C for 20 min. The exposure obtained from the home TLDs were calculated as follows:

$$\left(\frac{R_{av}}{h}\right)(CF)(1000) = \text{microR/h}$$

where

$$CF = \text{correction factor} = \frac{100 \text{ milliR/h}}{\underset{\text{(milliR)}}{\text{irradiated control TLD} - \text{background TLD}}},$$

R_{av} = average of the two TLD readout values,

h = number of hours at location,

1000 = conversion factor to obtain microrems.

2.3 Placement of TLDs

Eighty-four homes in the Oak Ridge/Knoxville area were used as TLD placement locations for this study (Fig. 2.2). The TLDs were taken home by volunteer Oak Ridge National Laboratory (ORNL) employees. These employees were instructed to place the TLD where their personnel dosimeter was placed after working hours. For a period of one year, each employee brought the TLD to ORNL quarterly for prompt reading. A replacement TLD was given to each participant.

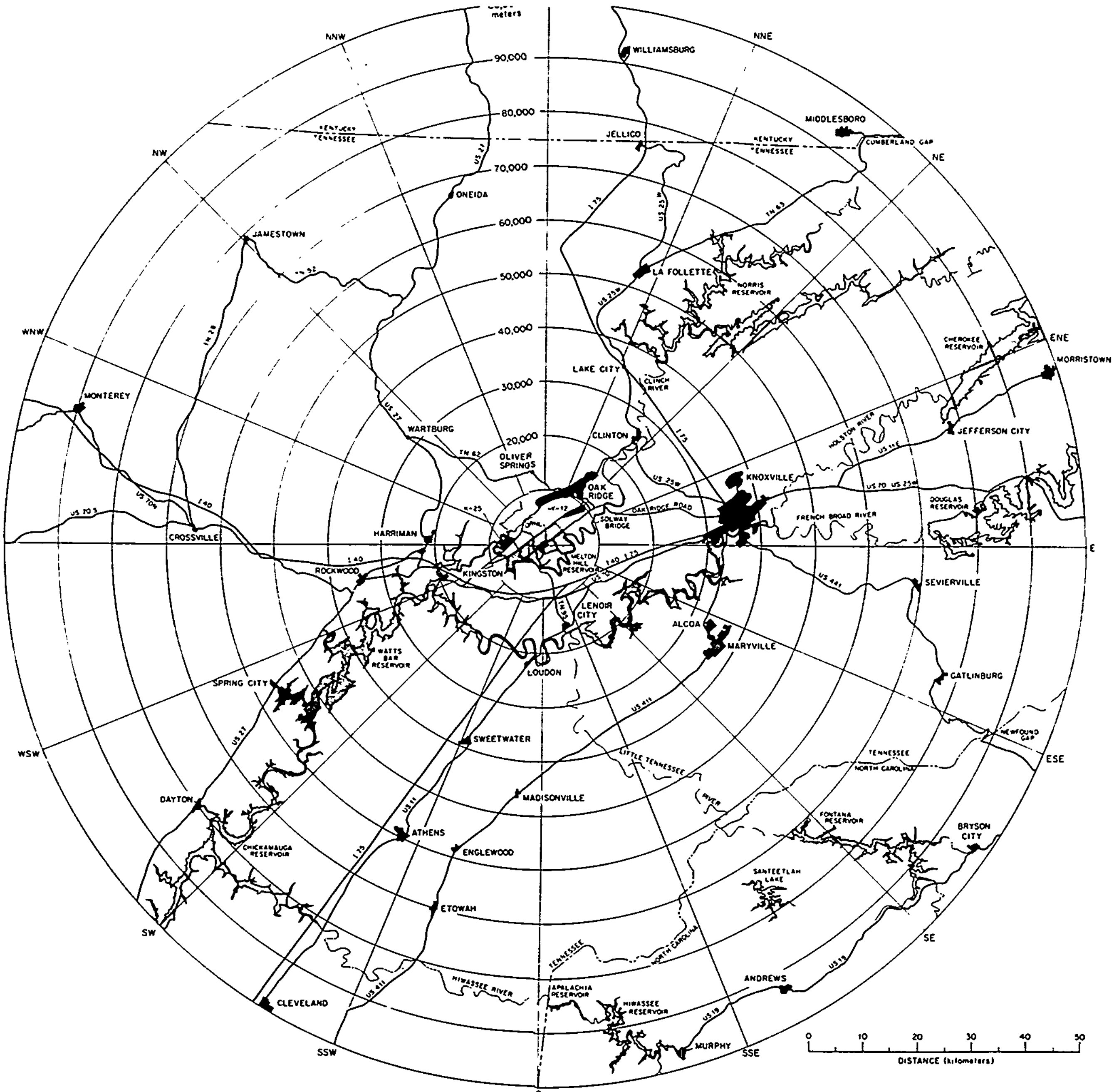

Fig. 2.2. Oak Ridge area.

3. RESULTS AND DISCUSSIONS

Data were collected and evaluated from the residences of ORNL employee-volunteers on a quarter-to-quarter basis. Descriptive information about each residence was obtained to correlate differences between dosimeter values and possible source terms. Characterization of each test home included principle building material, geographic location, and insulation and storm window additions. The data generated by this investigation are presented in Appendix A. The TLDs were placed into polyethylene bottles containing silica gel and located inside each test home so that variations in TLD readings could be kept to a minimum. TLD-100s were used because of their slow-fading characteristics.

3.1 General Observations

Analysis of the data indicated that several parametric variations must be considered including season, geographic location, and building material. Seasonal variation of dose determined from the TLD readings can be seen in all types of residences. In this study, fall is defined as October 1 through December 31, winter as January 1 through March 31, spring as April 1 through June 30, and summer as July 1 through September 30. The highest average TLD reading reported was in the fall, while the lowest was in the spring (Fig. 3.1).

Predictably higher dose values were obtained in brick (stone) homes than in houses made principally of wood (Figs. 3.2 and 3.3). Both types of houses showed approximately the same trend of seasonal variations including higher TLD readings in the fall and lower values in the spring. The higher dose values in brick (stone) houses were probably caused by the atmospheric increase of radon-emanation from the stone itself. Three control TLDs were placed in basements located in Knoxville, Oak Ridge, and Kingston to show an increased dose from radon emanation from stone. An average dose equivalent rate of 11.9 ± 1.4 microrems/h or

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*This can be compared to the average background dose of 78 ± 3.3 millirems per year calculated from this study.

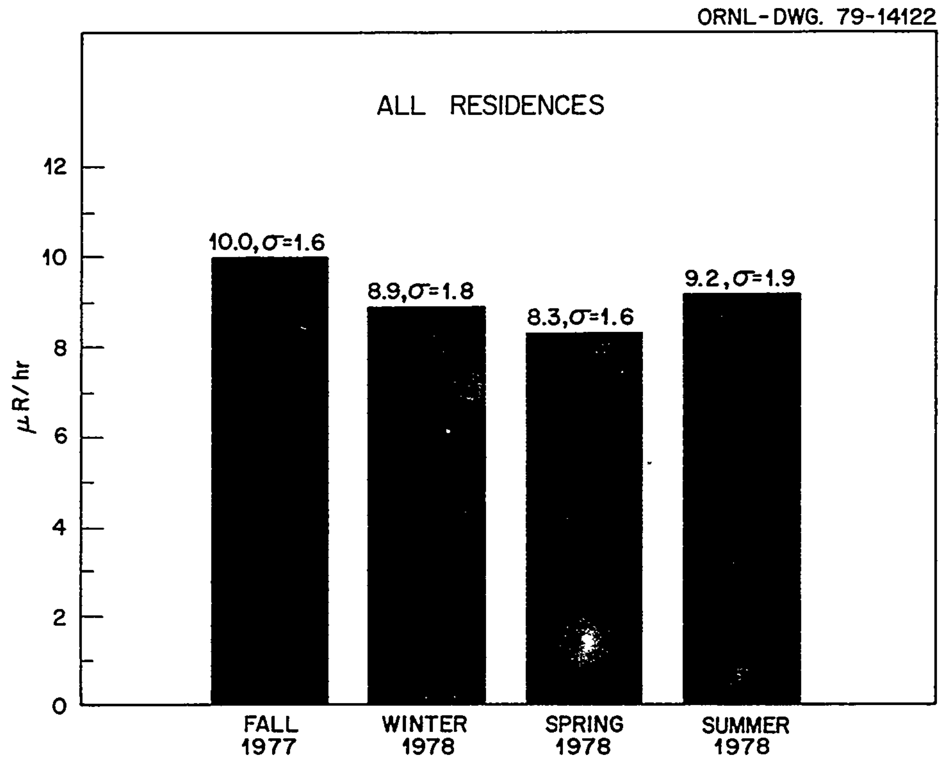

Fig. 3.1. Seasonal variations of TLD readings among all test homes.

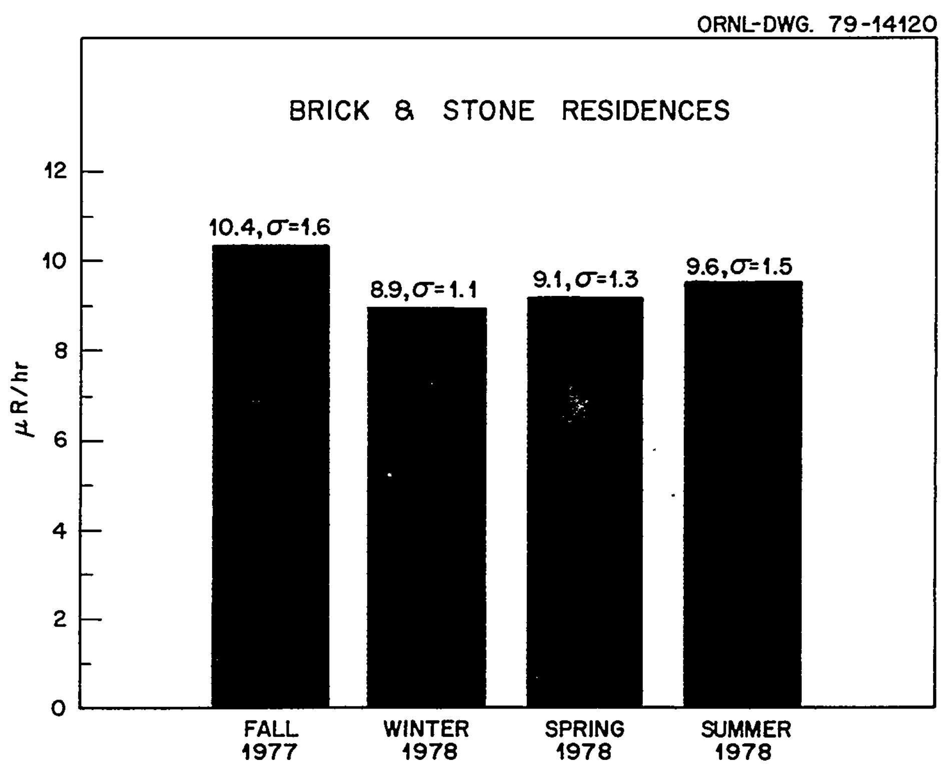

Fig. 3.2. Seasonal variations of TLD readings in brick and stone test homes.

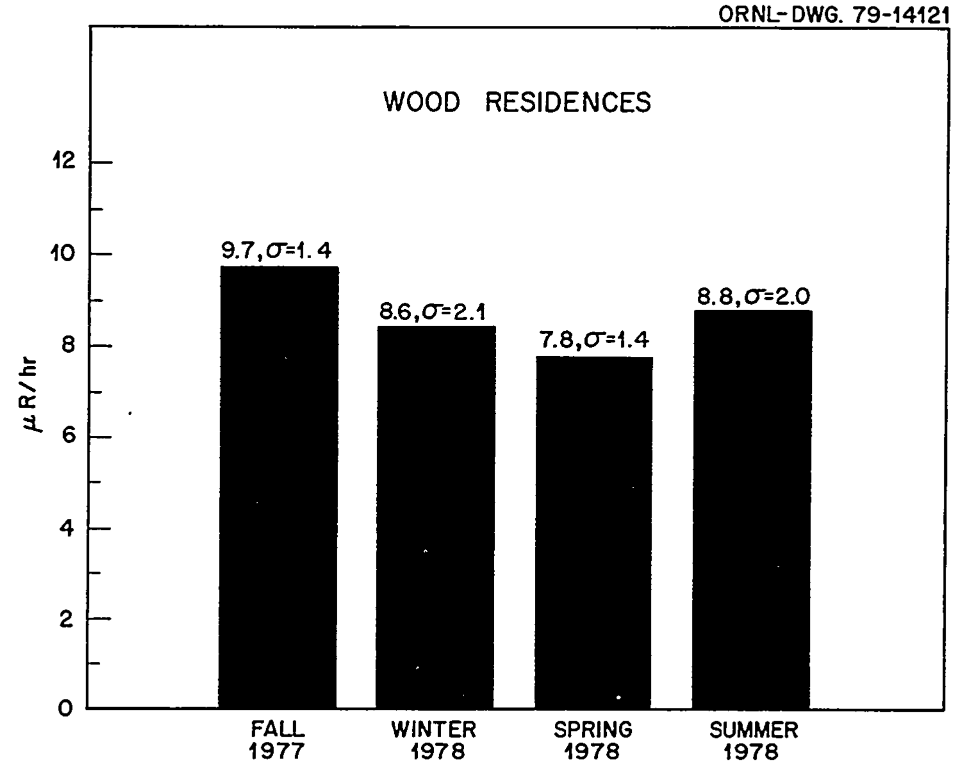

Fig. 3.3. Seasonal variations of TLD readings in wood test homes.

104.6 millirems/year was obtained.* These higher dose equivalent rate values were attributed to the enhancement of radon concentration caused by decreased ventilation and increased stone content.

Another parameter that appeared to affect the exposure was geographic location. Table 3.1 shows the quarterly and yearly dose values determined as a function of geographic location. All the yearly dose rates were within two standard deviations about the mean. However, it is interesting to note that the higher dose was not obtained in Oak Ridge, which is in close proximity to a complex of nuclear facilities. The average dose equivalent rate obtained from this area is 78 ± 3.4 milliR per year. This dose rate compares favorably to the average natural background radiation in the United States of approximately 125 milliR per year.

Other factors influencing the dose rates obtained included fluctuations in temperature, humidity, ventilation rate, heating, air conditioning, etc. Data obtained from homes with additional insulation (compared

Table 3.1. Dose equivalent rates calculated from various locations in the Oak Ridge area

Location	Quarter[a]				Average microrems per hour[b]	Average millirems per year
	1 (fall 1977)	2 (winter 1978)	3 (spring 1978)	4 (summer 1978)		
Knoxville	10.2 ± 1.8	9.1 ± 2.6	8.5 ± 2.1	9.6 ± 2.3	9.4 ± 0.7	82
Oak Ridge	9.9 ± 1.7	8.5 ± 1.0	7.9 ± 1.4	9.1 ± 1.9	8.9 ± 0.9	78
Kingston	9.9 ± 1.7	9.2 ± 1.6	8.7 ± 0.5	9.4 ± 2.2	9.3 ± 0.5	82
Clinton	10.1 ± 1.1	8.8 ± 1.3	8.1 ± 1.4	8.9 ± 1.9	9.0 ± 0.9	79
Oliver Springs	9.2 ± 0.7	7.9 ± 0.0	8.6 ± 1.6	8.6 ± 1.1	8.6 ± 0.5	75
Lenoir City	9.8 ± 1.8	8.4 ± 1.9	7.6 ± 1.4	8.8 ± 1.4	8.6 ± 0.9	75
Powell	9.4 ± 0.7	7.9 ± 1.1	8.0 ± 1.0	8.4 ± 0.8	8.3 ± 0.5	73
Miscellaneous towns	10.4 ± 2.1	10.2 ± 1.4	9.6 ± 0.8	8.8 ± 1.1	9.7 ± 0.7	85

[a] ± standard deviation of the average of TLDs per quarter.

[b] ± standard deviation of the average of the four quarters.

to homes that were normally insulated) showed no correlation to dose rate (Figs. 3.4 and 3.5). This result was probably caused by the sensitivity of the test method.

At ORNL, the personnel dosimeter is located inside the security badge. After a working day, the employee arrives at home and places his dosimeter in the home. This study measured the natural background radiation dose was obtained by this method of badge storage. Therefore, only dose rates of a background level were detected by this study.

3.2 Statistical Analysis

A statistical model was developed using the data of this study to predict dose rates in the Oak Ridge area. The variations in dose rates at the test locations could be attributed to many factors, including groundwater composition and geologic formations. It has been shown that the ^{40}K concentrations in the soil vary by a factor of 400 in the East Tennessee area.[24]

Several linear models and their ability to explain the variation in the background radiation levels were investigated using the method of multiple linear regression via generalized least squares. An acceptable model was used to obtain point estimates and confidence intervals for the mean natural background radiation levels for several of the residences studied.

In a multiple regression setting, several independent variables are assumed to determine, to some extent, the observed value of a particular dependent variable of interest. Here, the value of the dependent variable (dosimeter measurement of background radiation) is assumed to depend on values of several independent variables (housing characteristics and quarters) that are set prior to observing the dependent variable. In a sense, the dependent variable is a function of the independent variables, so background radiation is a function of housing characteristics and quarters.

The first model was used to investigate the independent variables of primary interest: quarter, geographic location, primary building material, and room in which the dosimeter was kept. A linear model

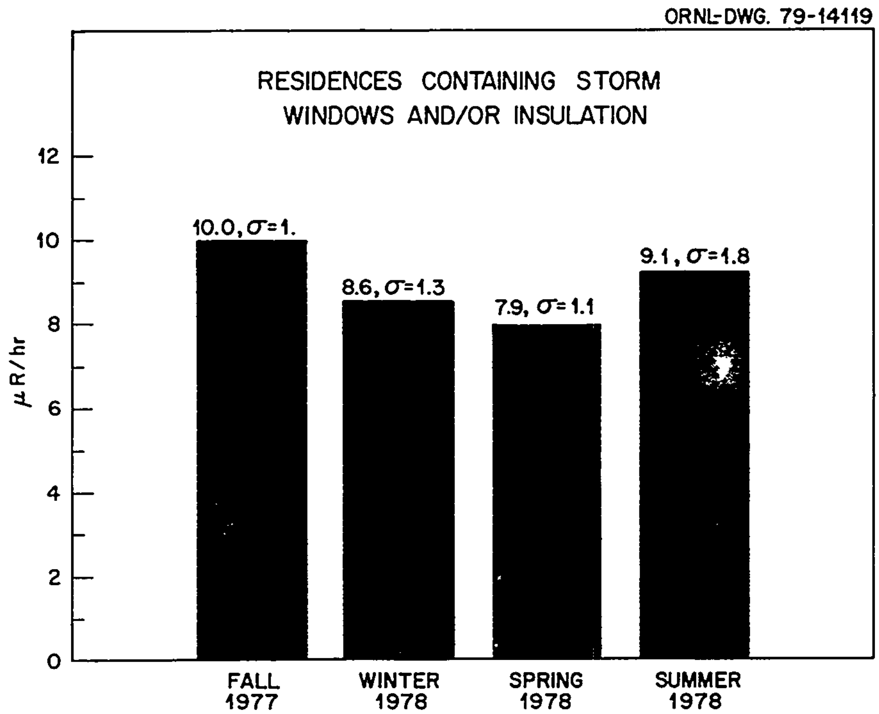

Fig. 3.4. Seasonal variations of TLD readings in test residences with respect to insulation and/or storm windows.

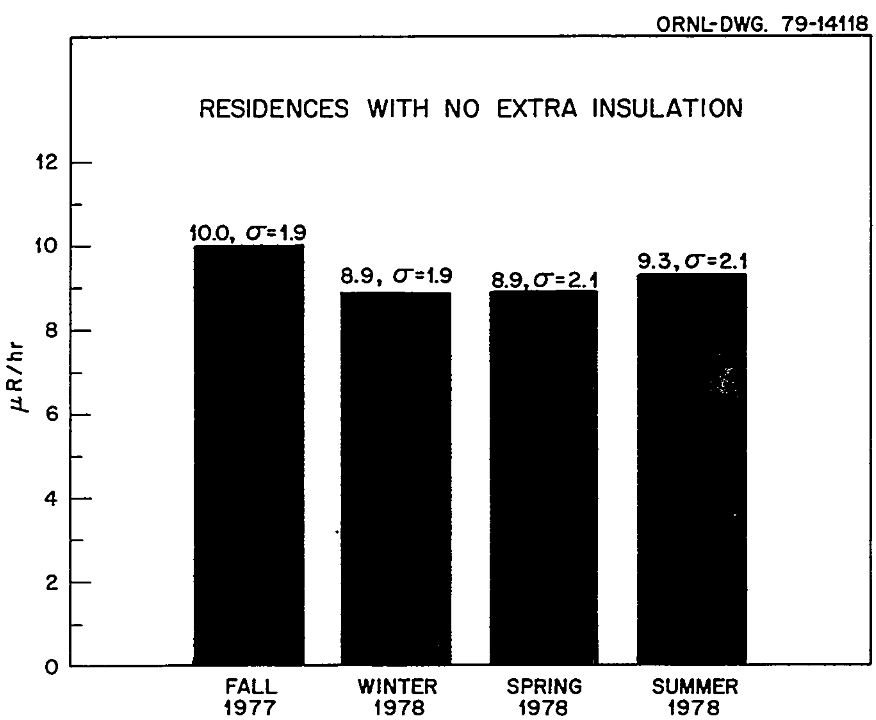

Fig. 3.5. Seasonal variations in test homes with no extra insulation.

using only the individual variables (as opposed to cross-products of two or more variables) was examined, and it indicated that all factors appeared statistically significant at the 5% significance level. However, it was of interest to investigate two measures of the adequacy of the model: (1) the possibility of increasing the multiple correlation coefficient and (2) the possibility of decreasing the coefficient of variation.

The second model involved the addition of the two-way interaction terms (i.e., cross-products of two variables) to the main effects model. However, the sparseness and confounding of the data as evidenced by the zero sums of squares that resulted did not permit use of this model.

It seemed reasonable to consider the data in a hierarchical scheme where rooms occur within house types and house types occur within towns of residence. The third model, the corresponding hierarchical model, was investigated and resulted in all variables testing significant and in an improved fit over the first model. This model was chosen as the most appropriate of the models studied after a few more alternatives were investigated and eliminated.

There was some concern over the assumption of normality of the data. In an attempt to improve the reasonableness of the assumption that the data were normal, the natural logarithm transformation was applied to the dependent variable, (background radiation) and the hierarchical model was investigated in this transformed setting. Although the transportation substantially reduced the coefficient of variation, the multiple correlation coefficient was only slightly improved. Moreover, there were considerable difficulties in interpreting the transformed model; thus it was removed from consideration.

The majority of the data came from Knoxville and Oak Ridge and from one room: the bedroom. It seemed likely that reducing the investigation to this subset might result in a more accurate model. Two house types (stone and aluminum) had to be eliminated to have representation of every house type in both towns. The hierarchical model was applied to this subset of the data, but the result was slightly worse than when the same model was applied to the entire data set. In addition, the natural logarithm transformation was applied to this subset, yet fitting the hierarchical model to the transformed data further reduced the fit. Counter to the prior notion, the subset models did not result in a more conclusive model.

As a final effort, the remaining housing characteristics (heating, air conditioning, and insulation) were added as main effects to the hierarchical model for the subset data set to determine if they had any effect on the level of background radiation observed. Because adding terms to any model necessarily improves the fit, the terms should remain in the model only if there is a substantial improvement. Heating and air conditioning were determined to be not significant in their contribution to the model and were eliminated. The last characteristic, insulation, appeared marginally significant, however the improvement in the model was quite small. Thus the expense of collecting the insulation data was not warranted by any sizeable increase in the accuracy of the model.

In conclusion, the hierarchical models for either the entire data set or the subset were the best of the models investigated as measured by the multiple correlation coefficient and the coefficient of variation. No significant improvement was obtained through either the addition of terms to the model or transformation of the dependent variable. The hierarchical model for the entire data set was somewhat better than the same model applied to the subset of data; thus, for simplicity and completeness, the model for the entire data set was preferred. Neither model will predict with great precision, yet they can predict approximate dose rate for the residences studied. The hierarchical model for the entire data set yielded a multiple correlation coefficient of approximately 0.53 and reduced the coefficient of variation from 20.08 to 14.62 with all variables significant at the 0.01 level. The hierarchical model for the subset of data yielded a multiple correlation coefficient of approximately 0.45 and reduced the coefficient of variation from 20.18 to 15.63% with all variables significant at the 0.01 level. One way to improve the precision of either model would be to collect data of a quantitative nature such as indoor/outdoor temperature and add this to the model. Unfortunately the scope of this particular study did not allow for such considerations. Table B.2 of Appendix B summarizes the models investigated.

3.2.1 Description of the hierarchical model

The model that was selected as the most appropriate in describing natural background radiation as a function of the characteristics studied has a hierarchical structure in that rooms occur within residences and residences within towns. The more common matrix representation of this linear model (rather than the subscription parameter notation) is given by

$$\vec{Y} = X\vec{\beta} + \vec{\varepsilon}$$

where $\vec{Y}$ is the vector of observed radiation levels, X is the design matrix of ones and zeros that indicate the housing characteristics for each observation, $\vec{\beta}$ is a vector of parameters or coefficients that are to be estimated, and $\vec{\varepsilon}$ is a vector of unobservable random errors. A vector solution to this equation is given in Appendix B, Table B.1. A description and example of the coding scheme and consequently the development of the design matrix also are given in Appendix B.

3.2.2 Estimation of mean natural background radiation

If the hierarchical model is assumed to be the correct model for the dependency of background radiation level on housing characteristics and quarters, then the mean background radiation levels for particular housing characteristics that occur in the data set are estimable and invariant. Several examples of estimated mean background radiation levels are given in Table 3.2. Similar calculations could be performed for other housing characteristics of interest that appear in the data set.

The confidence intervals are interpreted to mean that there is approximately 95% confidence that the true mean background radiation level for the particular housing configuration lies in the interval given. The confidence intervals are of use in interpreting mean dosimeter

Table 3.2. Estimation of mean background radiation in bedrooms using the hierarchical model on the entire data set for the first quarter

Housing configuration and location	Point estimate of mean background radiation level (milliR)	Approximate 95% confidence interval for the mean
Brick, Knoxville	10.5	(10.0, 11.1)
Brick, Oak Ridge	9.8	(8.8, 10.7)
Concrete, Knoxville	13.5	(12.5, 14.6)
Concrete, Oak Ridge	10.3	(9.5, 11.1)
Cemesto,[a] Oak Ridge	9.8	(9.2, 10.4)

[a]Asbestos type.

readings to indicate whether the observed mean for houses of a particular configuration is more likely from natural background radiation or from some anomalous occurrence.

SUMMARY

Eighty-four residences in the Oak Ridge area were used to determine radiation exposure indoors during one year. All residences showed seasonal variations in dose rates; the highest TLD values were reported in the fall and lowest in the spring. Higher values were obtained from houses principally comprised of brick (stone) compared with dose rates obtained in wooden residences. Variances in dose values were also noted with respect to geographic location of the test homes. An important result of these variances showed that Oak Ridge residences, although close to a complex of nuclear facilities, had a dose equivalent rate of 78 milliR per year. This result can be compared to the mean dose equivalent rate from all the test residences outside of Oak Ridge which read 79 milliR per year. Other factors, such as insulation additions and storm windows, had no detectable variations in dose rates. A statistical model was developed to explain the data obtained and to predict dose rates given certain housing characteristics and geographic locations.

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APPENDIX A

INDIVIDUAL HOUSE DATA

The following data were compiled from the participants in the study. The following code is used in the table.

WD — Wood
BR — Brick
CM — Cemesto
CR — Concrete
AL — Aluminum or Mobile Home
I — Insulation
S — Storm Window
N — No Insulation or Storm Window
BR — Bedroom
LR — Living Room
BAS — Basement
ND — Not Determined

Table A.1. Quarterly results
(μR/h)

TLD No.	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Average	Standard deviation	Type of house	Type of heat	Air conditioning	Insulation	Location of TLD
						Residents of Oak Ridge					
407	12.3	11.3	9.7	12.5	11.5	1.3	BR	Gas	Yes	N	BAS
408	8.7	7.3	6.9	6.8	7.4	0.9	CM	Gas	Yes	I	BR
409	8.7	7.9	6.9	8.9	8.1	0.9	WD	Electric	Yes	I	BR
410	8.7	7.3	6.5	8.9	7.9	1.2	WD & BR	Electric	Yes	N	BR
411	7.7	8.5	6.0	6.9	7.3	1.1	WD	Gas	Yes	N	BR
413	10.8	8.5	8.3	8.4	8.9	1.2	WD	Steam	No	S	BR
414	7.2	7.9	8.3	6.9	7.6	1.6	WD	Gas	No	N	BR
416	8.7	7.9	7.9	8.4	8.2	0.4	WD & BR	Gas	Yes	ND	ND
420	12.8	10.7	10.4	12.1	11.5	1.1	CR	Electric	No	I,S	BR
430	11.8	10.2	8.6	11.2	10.4	1.4	CM & WD	Electric	Yes	I	BR
432	11.3	7.3	6.0	11.0	8.9	2.6	WD	Electric	No	N	BR
436	12.8	8.5	ND	ND	10.6	3.1	WD	Gas	No	ND	ND
438	9.2	7.3	6.0	8.4	7.7	1.4	CM	Gas	Yes	I	BR
443	8.7	7.9	8.3	7.8	8.2	0.4	CR	Electric	Yes	N	BR
444	13.3	9.6	9.3	7.8	10.0	2.4	CM	Electric	Yes	I,S	BR
446	9.7	7.9	7.4	7.8	8.2	1.0	BR	Electric	Yes	I,S	BR
448	10.3	8.5	10.7	8.3	9.4	1.2	BR	Oil & WD	Yes	N	BR

Table A.1 (continued)

TLD No.	Quarter 1	2	3	4	Average	Standard deviation	Type of house	Type of heat	Air conditioning	Insulation	Location of TLD
449	10.3	8.5	6.9	12.0	9.4	2.2	BR	Electric	Yes	I,S	LR
451	12.8	9.0	6.9	8.9	9.4	2.5	CM	Gas & Electric	Yes	I	BR
464	11.2	8.5	6.9	12.5	9.8	2.5	WD	Gas	No	ND	ND
465	9.7	10.2	11.1	12.5	10.9	1.2	CM	Electric	Yes	N	BR
467	9.2	8.5	7.4	7.8	8.2	0.8	WD	Gas	Yes	N	BR
472	8.2	7.9	7.4	7.8	7.8	0.3	CM	Gas	Yes	I	BR
474	8.2	7.9	6.9	ND	7.7	0.7	BR & Masonite	Electric	Yes	ND	ND
477	9.7	9.0	7.4	ND	8.7	1.2	CM	Gas	Yes	ND	ND
482	10.3	9.0	6.9	8.6	8.7	1.2	WD	Electric	Yes	N	BR
488	8.7	8.5	8.3	8.4	8.5	0.2	WD	Electric	Yes	N	BR
490	8.7	7.9	9.3	7.8	8.4	0.7	WD	Electric	Yes	N	BR
493	8.7	8.5	8.3	8.4	8.5	0.2	CR	Steam	No	N	BR
495	9.2	8.5	8.3	8.4	8.6	0.4	WD	Electric	Yes	I,S	BR
						Residents of Knoxville					
403	8.2	6.8	6.5	8.4	7.5	1.0	WD & BR	Electric	Yes	N	BR
405	8.7	7.3	6.5	7.8	7.6	0.9	WD	Electric	Yes	S	BR
406	8.2	7.3	7.9	6.9	7.6	0.6	WD & Stone	Electric	Yes	I	BR
412	8.7	9.0	9.3	11.5	9.6	1.3	BR	Electric	Yes	N	BR
418	9.2	7.3	ND	8.4	8.3	1.0	BR	Electric	Yes	N	BR

Table A.1 (continued)

TLD No.	Quarter 1	2	3	4	Average	Standard deviation	Type of house	Type of heat	Air conditioning	Insulation	Location of TLD
419	9.2	7.9	9.3	10.4	9.2	1.0	WD	Electric	Yes	ND	ND
422	8.7	7.9	6.5	7.3	7.6	1.0	WD	Oil	No	S	Kitchen
426	11.3	18.1	6.0	9.9	11.3	5.0	WD	Gas	Yes	ND	ND
435	9.2	7.4	6.9	11.5	8.8	2.1	WD & BR	Electric	Yes	I	BR
437	12.8	10.7	10.2	10.2	11.0	1.3	BR	Electric	No	S	BR
442	9.2	7.9	7.4	7.8	8.1	0.8	WD & BR	Gas	Yes	I	BR
447	8.7	7.9	7.9	8.4	8.2	0.4	WD	Electric	Yes	S	LR
452	11.8	7.3	12.0	12.5	10.9	2.4	WD	WD	No	N	DR
456	11.8	8.5	7.9	7.3	8.9	2.0	BR	WD	No	N	BR
458	13.3	13.5	7.4	ND	11.4	3.5	CR	Electric	Yes	S	BR
461	11.3	7.3	6.9	8.9	8.6	2.0	BR	Electric	Yes	N	BR
463	11.3	9.0	7.1	7.4	8.7	1.9	WD	Electric	Yes	S	BR
469	9.2	9.0	7.4	9.3	8.8	0.9	AL & WD	Electric	Yes	S	BR
470	13.9	14.7	12.0	13.2	13.4	1.1	CR	Electric	Yes	N	BR
475	9.2	7.9	9.3	9.4	9.0	0.7	BR	Electric	Yes	ND	ND
476	10.3	9.0	ND	15.5	11.6	3.5	WD	WD	Yes	S	BR
478	10.3	8.5	8.3	8.9	9.0	0.9	BR	Electric	Yes	ND	ND
481	9.7	ND	8.3	9.9	9.3	0.9	BR	Gas	Yes	N	BR
483	14.4	9.0	12.5	12.0	12.0	2.2	BR	Gas	Yes	N	BR
484	8.7	7.9	8.3	7.2	8.1	0.6	WD	Gas	Yes	I	BR

Table A.1 (continued)

TLD No.	Quarter 1	2	3	4	Average	Standard deviation	Type of house	Type of heat	Air conditioning	Insulation	Location of TLD
486	9.2	8.5	7.4	7.8	8.2	0.8	WD & BR	Electric	Yes	ND	ND
489	12.3	13.5	14.8	13.6	13.6	1.0	BR & Masonite	Gas	Yes	N	BAS
491	9.7	9.6	8.3	7.3	8.7	1.2	BR	Electric	Yes	ND	ND
492	8.7	9.0	9.3	8.7	8.9	0.3	BR	Electric	No	N	BR
427	8.8	7.3	7.4	ND	7.8	0.8	WD	Electric	Yes	ND	ND
Residents of Powell and Concord											
415	9.7	8.5	7.9	8.9	8.7	0.8	Stone	Oil	Yes	ND	ND
417	8.7	6.2	7.4	7.3	7.4	1.0	AL	Electric	No	N	BR
423	8.1	ND	ND	8.9	8.5	0.6	BR	Electric	No	S	BR
454	9.8	7.3	7.4	9.4	8.5	1.3	WD	Gas	Yes	I	BR
487	8.7	8.5	7.4	7.8	8.1	0.6	WD	Gas	Yes	S	BR
497	9.2	9.0	9.7	8.4	9.1	0.6	BR	Electric	Yes	N	BR
Residents of Kingston											
401	9.2	6.8	8.8	8.2	8.3	1.1	WD	Electric	Yes	S	BR
402	9.8	10.2	8.8	11.0	9.9	0.9	BR	Electric	Yes	S	BR
431	8.2	9.6	8.0	6.8	8.2	1.2	AL	Electric	Yes	ND	ND
441	12.3	10.2	9.3	11.5	10.8	1.4	BR	Electric	Yes	N	BAS

Table A.1 (continued)

TLD No.	Quarter 1	2	3	4	Average	Standard deviation	Type of house	Type of heat	Air conditioning	Insulation	Location of TLD
					Residents of Lenoir City						
424	12.3	10.7	9.7	10.6	10.8	1.1	BR	Electric	Yes	ND	ND
434	9.7	7.9	6.9	8.4	8.2	1.2	WD	Electric & Gas	Yes	S	BR
440	8.7	6.2	6.9	7.3	7.3	1.1	WD	Gas	Yes	ND	ND
445	8.2	7.3	6.9	8.9	7.8	0.9	AL & WD	Electric	Yes	N	BR
					Residents of Clinton						
425	9.7	7.9	7.4	8.9	8.5	1.0	WD	Electric	Yes	S	BR
428	11.8	8.5	9.3	11.5	10.3	1.6	BR	Gas	Yes	S	BR
479	9.2	7.9	6.4	6.9	7.6	1.2	WD	Electric	Yes	S	BR
496	9.7	10.7	9.3	8.2	9.5	1.0	WD	Electric	Yes	N	BR
					Residents of Oliver Springs						
421	8.7	7.9	9.7	9.4	8.9	0.8	BR	Electric	Yes	I	BR
450	9.7	7.9	7.4	7.8	8.2	1.0	WD & BR	Gas	Yes	S	BR

Table A.1 (continued)

TLD No.	Quarter 1	2	3	4	Average	Standard deviation	Type of house	Type of heat	Air conditioning	Insulation	Location of TLD
					Residents of miscellaneous towns						
404	8.7	8.5	9.7	9.9	9.2	0.7	BR	Electric	Yes	I,S	BR
455	12.8	11.8	10.6	7.6	10.7	2.3	WD	Electric & WD	Yes	N	BR
457	11.3	10.2	9.3	9.4	10.0	0.9	BR	Electric	Yes	S	BR
459	8.6	10.2	8.8	8.1	8.9	0.9	WD	Electric	No	S	BR

APPENDIX B

SOLUTION OF THE HIERARCHICAL MODEL

In the quantitative least squares situation, the solution to the regression equation $\vec{Y} = X\vec{\beta} + \vec{\varepsilon}$ is given by $\vec{b} = (X'X)^{-1} X'\vec{Y}$, the normal equations. However, in the quantitative situation, the $(X'X)$ matrix is singular and no inverse exists to solve the equation. To find a solution, a generalized inverse matrix must be obtained by deleting some number of rows of the $(X'X)$ matrix, which is equivalent to setting some of the parameters in the vector $\vec{b}$ equal to zero. The resulting estimates, say $\vec{b}°$, are biased and do not estimate the original parameters, however they are the best linear unbiased estimators of some linear combination of parameters in the model. Fortunately, the means of residences of particular housing configurations are estimable and invariant to whatever solution, $\vec{b}°$, that is chosen.

The estimates for the hierarchical model were obtained through the Statistical Analysis System[26] and are given in Table B.1.

Table B.1 provides the key to the coding scheme used and hence the design matrix, X. There are 71 dummy variables in the model that are individually coded as either one or zero. For each observation, each dummy variable is coded as one if the observation has the corresponding characteristic or as zero if not. For example, an observation from a cemesto house in Oak Ridge in the bedroom in the first quarter would have ones coded into the following dummy variables

X_1, representing the overall mean for all observations
X_2, representing the first quarter
X_{11}, representing Oak Ridge
X_{30}, representing cemesto houses in Oak Ridge
X_{62}, representing bedrooms in cemesto houses in Oak Ridge

with zeroes assigned to the remaining 68 dummy variables. All observations were coded in the same manner, and the matrix of the resulting coded observations is the design matrix, X. In fact, the vectors coded in this manner are exactly the vectors $\vec{q}$ used to estimate the means.

Table B.1. A solution to the hierarchical model
(Intercept solution — 8.359, dummy variable 1)

Dummy variable subscript	Quarter	Corresponding characteristics in the model			Solution[a]
		City	Building material	Room	
2	1				0.875
3	2				-0.386
4	3				-0.769
5	4				0.000
6		Clinton			0.240
7		Kingston			-0.031
8		Knoxville			-0.729
9		Lenoir City			-0.451
10		Miscellaneous			1.523
11		Oak Ridge			-0.441
12		Oliver Springs			-0.071
13		Powell			0.000
14		Clinton	Brick		1.716
15		Clinton	Wood		0.000
16		Kingston	Brick		1.670
17		Kingston	Wood		0.000
18		Knoxville	Brick		2.029
19		Knoxville	Brick-Masonite		5.995
20		Knoxville	Concrete		5.021

Table B.1 (continued)

Dummy variable subscript	Quarter	Corresponding characteristics in the model			Solution[a]
		City	Building material	Room	
21		Knoxville	Wood		0.648
22		Knoxville	Wood-Aluminum		1.185
23		Knoxville	Wood-Brick		0.537
24		Knoxville	Wood-Stone		0.000
25		Lenoir City	Wood		0.395
26		Lenoir City	Wood-Aluminum		0.000
27		Miscellaneous	Brick		-0.201
28		Miscellaneous	Wood		0.000
29		Oak Ridge	Brick		1.570
30		Oak Ridge	Cemesto		1.036
31		Oak Ridge	Cemesto-Wood		2.575
32		Oak Ridge	Concrete		1.533
33		Oak Ridge	Wood		0.472
34		Oak Ridge	Wood-Brick		0.000
35		Oliver Springs	Brick		0.715
36		Oliver Springs	Wood-Brick		0.000
37		Powell	Aluminum		-0.891
38		Powell	Brick		0.419
39		Powell	Wood		0.000
40		Clinton	Brick	Bedroom	0.000

Table B.1 (continued)

Dummy variable subscript	Quarter	Corresponding characteristics in the model			Solution[a]
		City	Building material	Room	
41		Clinton	Wood	Bedroom	0.000
42		Kingston	Brick	Basement	0.870
43		Kingston	Brick	Bedroom	0.000
44		Kingston	Wood	Bedroom	0.000
45		Knoxville	Brick	Bedroom	0.000
46		Knoxville	Brick-Masonite	Basement	0.000
47		Knoxville	Concrete	Bedroom	0.000
48		Knoxville	Wood	Bedroom	0.074
49		Knoxville	Wood	Dining Room	2.710
50		Knoxville	Wood	Kitchen	-0.608
51		Knoxville	Wood	Living Room	0.000
52		Knoxville	Wood-Aluminum	Bedroom	0.000
53		Knoxville	Wood-Brick	Bedroom	0.000
54		Knoxville	Wood-Stone	Bedroom	0.000
55		Lenoir City	Wood	Bedroom	0.000
56		Lenoir City	Wood-Aluminum	Bedroom	0.000
57		Miscellaneous	Brick	Bedroom	0.000
58		Miscellaneous	Wood	Bedroom	0.000
59		Oak Ridge	Brick	Basement	2.040
60		Oak Ridge	Brick	Bedroom	-0.594

Table B.1 (continued)

Dummy variable subscript	Quarter	Corresponding characteristics in the model			Solution[a]
		City	Building material	Room	
61		Oak Ridge	Brick	Living Room	0.000
62		Oak Ridge	Cemesto	Bedroom	0.000
63		Oak Ridge	Cemesto-Wood	Bedroom	0.000
64		Oak Ridge	Concrete	Bedroom	0.000
65		Oak Ridge	Wood	Bedroom	0.000
66		Oak Ridge	Wood-Brick	Bedroom	0.000
67		Oliver Springs	Brick	Bedroom	0.000
68		Oliver Springs	Wood-Brick	Bedroom	0.000
69		Powell	Aluminum	Bedroom	0.000
70		Powell	Brick	Bedroom	0.000
71		Powell	Wood	Bedroom	0.000

[a] The above estimates represent only one of many solutions to the normal equations. The estimates are biased and do not estimate the parameter but are the best linear unbiased estimates for some linear combination of parameters.

Table B.2 summarizes the models investigated giving several items of information about each one. Model 3, the preferred model in this investigation, is the hierarchical model for the entire data set.

Table B.2. Summary of models

Model number	Dependent variable	Variables in the model	Number of observations	Number of paramaters	Multiple correlation coefficient	Coefficient of variation[a]
1	Background radiation (entire data set)	Quarter Town Primary building material (PBM) Room	265	28	0.47	15.11 (20.08)
2	Background radiation (entire data set)	Quarter Town PBM Room Town & PBM Town & Room PBM & Room	265	84	(insufficient data to fit this model)	
3	Background radiation (entire data set)	Quarter Town PBM within Town Room within PBM within Town	265	71	0.53	14.62 (20.08)
4	Natural logarithm of background radiation (entire data set)	(same as model 3)	265	71	0.51	6.45 (8.62)
5	Background radiation (subset of data set)	(same as model 3)	163	19	0.45	15.63 (20.18)
6	Natural logarithm of background radiation (subset of data set)	(same as model 5)	163	19	0.44	6.83 (8.72)
7	Background radiation (subset of data set)	(same as model 5) Heat Air conditioning Insulation	163	31	0.51	15.18 (20.18)

[a]The number given in parentheses is the coefficient of variation for the data set before fitting the model.

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75–82. F. S. Tsakeres, Georgia Institute of Technology, Atlanta, GA 30332
83. J. F. Wing, DOE-ORO, Oak Ridge, TN 37830
84–329. Given distribution as shown in TID-4500 under Health and Safety Category UC-41